Change in the shrinkage forces of composite resins according to controlled deflection

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먼저 부족한 저를, 마지막까지 아낌없는 지도와 격려로 이끌어주신 박성호 지도교수님께 진심으로 감사드립니다. 교수님의 소중한 가르침으로, 쉽지 않은 연구주제에 도전하고 연구하여 이렇게 박사 논문을 마무리 할 수 있었습니다. 그리고 논문 심사를 맡아주시고 소중한 충고와 조언을 해주신 박정원 교수님, 신유석 교수님, 김광만 교수님, 권재성 교수님께도 진심으로 감사드립니다.

보존과 수련부터 대학원 마무리 과정까지 관심과 애정으로 지켜봐주신 이승종 교수님, 이찬영 교수님, 노병덕 교수님, 박성호 교수님, 김의성 교수님, 정일영 교수님, 박정원 교수님, 신수정 교수님, 신유석 교수님, 김선일 교수님, 김도현 교수님께도 이 자리를 빌어 감사의 마음을 전합니다.

수련과정부터 힘들때마다 항상 응원해준 보존과 동기들과 선후배들에게도 감사의 말을 전합니다.

항상 믿고 지켜봐 주시고 저를 이렇게 키워주신 사랑하는 부모님께 이 자리를 빌어 평소에 하지 못한 감사의 말씀을 올립니다. 마지막으로, 만학도 남편을 묵묵히 써포트 해주고, 존재만으로 큰 힘이 되어주고 늘 함께 해주는 아내 정서영, 세상 무엇과도 바꿀 수 없는 보물인 유동현, 유윤우, 유수아에게 글로는 다 표현하지 못할 깊은 사랑과 감사의 마음을 전합니다.

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유 일 상

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Abstract

Change in the shrinkage forces of composite resins according to controlled deflection

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As a tooth restoration material, the composite resin undergoes polymerization shrinkage, and polymerization shrinkage generates polymerization shrinkage force on the teeth under confinement due to bonding to cavity walls. Clinically, polymerization shrinkage and shrinkage force can cause debonding, marginal gap formation, microleakage, secondary dental caries, post-operative hypersensitivity, and cuspal deflection. In this study, especially with regard to cuspal deflection, the author investigated how the polymerization shrinkage forces of composite resins change with change in deflection. Five composites, SDR®

(Dentsply Caulk, Milford, DE, USA), EcuSphere-Shape (DMG, Hamburg, Germany), Tetric N-Ceram® Bulk Fill (Ivoclar Vivadent, Schaan, Liechtenstein), CLEARFIL™ AP-X (Kuraray Noritake Dental Inc., Sakazu, Kurashiki, Okayama, Japan), and Filtek™ Z350 XT (3M Dental Products, St Paul, MN, USA), were tested in this experiment. The polymerization shrinkage forces of the composites were measured using a custom-made tooth deflection-mimicking device and software (R & B Inc., Daejon, Korea). In all measurements, six modes were tested, comprising maximum-deflection, zero-deflection, and four deflection-controlled modes. For each deflection mode, the shrinkage forces were recorded continuously every 0.1 for 180 s. Polymerization shrinkage and flexural modulus were also measured. Eight specimens of each material were allocated for each test. For each material, six groups of shrinkage force values were compared using one-way ANOVA and Tukey's post hoc tests at a 95% confidence level. The polymerization shrinkage force of each material in each of the six deflection modes was analysed with 95% confidence using one-way ANOVA and Tukey's post hoc tests. The relationship between the force measured in the six deflection modes and the linear polymerization shrinkage and flexural modulus was analysed with 95% confidence using Pearson’s correlation analysis. For each material, the following held true: the shrinkage force was highest in zero-deflection mode, the force decreased as deflection increased, and the smallest force appeared in maximum-deflection mode ($P<0.05$). There was a high negative correlation between allowable deflection and shrinkage force in all materials. Polymerization shrinkage forces and the differences in such forces between composite resins decrease with increasing cuspal deflection. When high

deflection is expected, controlling composite volume with a base material or use of a layer filling technique are more practical than trying to choose a composite with low polymerization shrinkage force.

Keywords: : C-factor, composite resin, cuspal deflection, polymerization shrinkage, polymerization shrinkage force, polymerization stress

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I. INTRODUCTION

As a direct restorative material, dental resin composites are widely used for anterior and posterior tooth restoration. However, one of the drawbacks of composites is that internal stress is inevitable due to the nature of vinyl polymerization, which involves

reductions in intermolecular dimensions and free volume (Ferracane and Hilton, 2016). Shrinkage stress in composite restorations results from polymerization shrinkage occurring under confinement due to bonding to cavity walls (Braga et al., 2005); confined shrinkage causes excessive residual stress that, if in tension, can cause micro-crack initiation and breakage (Feilzer et al., 1987; Watts et al., 2003; Weinmann et al., 2005). Polymerization shrinkage and contraction stress can cause debonding, marginal gap formation, microleakage, secondary dental caries, post-operative hypersensitivity, and cuspal deflection (Schneider et al., 2010). More than 1% of polymerization shrinkage is unpreventable despite substantial shrinkage reduction efforts (Weinmann et al., 2005).

Polymerization shrinkage stress in composite resins was first studied as a function of restoration shape (Feilzer et al., 1987) Shape was described with a configuration factor, C, representing the ratio of the restoration's bonded to unbonded (free) surfaces. In that experimental set-up, the shape of the restoration was simulated with cylindrical forms of various dimensions and shrinkage stress was continuously measured. Any axial sample contraction, which occurs due to yielding of the load cell to the shrinkage force, was immediately counteracted and the height of the cylindrical forms was maintained with a feedback mechanism. Under these low compliance conditions, polymerization shrinkage stress increased as C-factor increased.

However, Watts et al (Watts and Satterthwaite, 2008) reported that the teeth and their cavities display elastic and visco-elastic compliance and that stress should be measured while allowing for minimal but essential compliance. In their non-stiff system, the

relationship between polymerization and C-factor is more complex than simply a ratio of bonded to unbonded surfaces. When polymerization stress was measured under non-stiff conditions, both C-factor and resin composite mass are important in the formation of shrinkage stress.

Less stress was recorded in a non-stiff system than under stiff conditions due to the stress-relieving effect of allowable displacement (Lu et al., 2004; Watts et al., 2003). In the high-compliance system, polymerization shrinkage stress decreased as C-factor increased. This tendency decreased as system compliance decreased and eventually reversed as higher C-factors increased polymerization shrinkage stress (Wang and Chiang, 2016).

It has been reported that placing composites in Class II cavity preparation leads to inward deformation of the cusps (Lee and Park, 2006). Cuspal deflection is the result of the interaction between composite resin polymerization shrinkage stress and cavity wall compliance when the adhesive force between tooth and composite resin is strong enough (Lee et al., 2007).

The structural and material factors that affect cuspal deflection are cavity width and depth, thickness of residual dentin (Lee et al., 2007; Meredith and Setchell, 1997), polymerization shrinkage of composite resin (Suliman et al., 1993), and flow and compliance of cured composite and teeth (Davidson and De Gee, 1984; Suliman et al., 1993). The clinical factors affecting cuspal deflection are use of a liner (Unterbrink and Liebenberg, 1999), filling technique (Lee et al., 2007; Rees et al., 2004), restoration method

(Lee et al., 2007; REES and JACOBSEN, 1992), and light curing method (Ericson et al., 1994).

Cuspal deflection varies from approximately 10 – 45 μm depending on measurement method, tooth type, cavity prepration type, and cavity size (Lee et al., 2007; Lee and Park, 2006). Even within a prepared cavity, deflection may vary according to remaining tooth structure and location in the cavity preparation. Thus, the relationship between polymerization shrinkage and deflection could have a significant clinical effect.

The purpose of this study was to develop an in vitro system that exhibits constant compliance but can also exhibit various deflections, mimicking cuspal deflection of the tooth and to evaluate the relationship between deflection and polymerization shrinkage force. In our experimental devices, the various amounts of deflection under shrinkage force can be controlled by feedback action.

The null hypotheses were:

1. Polymerization shrinkage force does not change, even if deflection changes.
2. Polymerization shrinkage force does not correlate with amount of polymerization shrinkage.
3. Polymerization shrinkage force does not correlate with flexural modulus.

II. MATERIALS AND METHODS

1. Materials

Five different composites were used in this experiment. (Table 1). Following the results of pilot study, one flowable bulk-fill (SDR®), one condensable bulk-fill (Tetric N-Ceram® Bulk Fill), two micro-hybrid (CLEARFIL™ AP-X, EcuSphere-Shape) and one nono-hybrid (Filtek™ Z350 XT) were selected with different elastic modulus.

2. Density Measurement

Each sample had a volume of 63 mm^3, which is equivalent to a 3 mm (width) X 3 mm (depth) X 7 mm (length) MOD cavity. Measurements were taken, first of the density of each material in order to apply the same volume of material, and second of the mass equivalent to the volume. Whilst pre-polymerization density is more accurate, post-polymerization density was used as flowable type SDR® was included as one of the samples, for which pre-polymerization density is hard to measure. The density of 5 specimens for each material, with 10 mm in diameter and 1 mm thick disks, were measured. Excellence XS Precision Balances (XS105, Mettler-Toledo International Inc., Greifensee, Switzerland) with Mettler Toled installed Density Accessory Kits were used in a laboratory environment. Specimen weights were measured on the pan in both air and distilled water.

Density, calculated according to Archimedes' principle, was recorded and average values determined. The measured density values are given in Table 1.

Table1. Composite resin materials used in this study

Brand Name	Manufacturer	LOT #	Density (g/㎤)	Filler content (wt/vol %)	Type
SDR®	Dentsply Detrey GmbH, Konstanz, Germany	1511000715	1.976 (0.005)	68/ 44	Bulkfill Flowable
EcuSphere-Shape	DMG, Hamburg, Germany	750594	2.039 (0.003)	77/ 57-	Packable
Tetric N-Ceram® Bulk Fill	Ivoclar Vivadent, Schaan, Liechtenstein	S14902	2.072 (0.028)	78/ 55	Bulkfill Packable
CLEARFIL™ AP-X	Kuraray Noritake Dental Inc., Sakazu, Kurashiki, Okayama, Japan	4J0073	2.332 (0.016)	86/ 70	Pacakable
Filtek™ Z350 XT	3M Dental Products, St Paul, MN, USA	N678112	1.915 (0.008)	78.5/ 59.5	Pacakable

Figures in the parentheses are standard deviations.
Composition of base resin and filler content are from manufacturer's information.

3. Polymerization Shrinkage Force Measurement and Deflection Control

The polymerization shrinkage forces of the resin composites were measured using a custom-made device (Figure 1) that can measure the force and lock the movement

according to a feedback mechanism that operates when it exceeds a specified displacement and software (R & B Inc., Daejon, Korea). The instrument was driven by a motor and was designed to move a metal bar up and down. An acrylic rod was screwed into the metal rod. A sensor (Figure 1B) was installed which could control the movement of the metal and acrylic rods (Figure 1C, D) by a feedback mechanism. Before placing the composite in the device, the surface of the acrylic rod was roughened with sandpaper (180 grit), treated with adhesive resin (bonding agent, AdheSE 2, Ivoclar Vivadent, Schaan, Liechtenstein), and light-cured. A restorative material (63 mm^3) was placed at the end of the acrylic rod. Its position was then adjusted with the motor, which was connected to the metal bar, until the thickness of the restorative material reached 2 mm (diameter: 6.4 mm, C-factor = 1.6). The force between the acrylic rod and the resin composite was set to zero using the software, and the resin composite was light-cured (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein, 800 mW/ Cm^2) for 20 s through the 1mm thick transparent acrylic base (Figure 1F). The deformation in the specimen during polymerization shrinkage is so small that it is negligible. When the polymerization shrinkage force was measured with a force cell (100 kgf) connected to the bar, the displacement of the rod was concomitantly recorded by a sensor with a resolution of 0.1 μm every 0.1 s for a total time of 180 s.The displacement of the rod was adjusted based on feedback using the installed software. The compliance of this system was 0.5 μm/N.

In the zero-deflection group (Group 1), when the feedback sensor (Figure 1B) detected more than 0.1 μm of downward movement of the metal and acrylic rods (Figure 1C, D)

during the polymerization process, the metal and acrylic rods were returned upwards to their original position via the feedback system. Thus, the system returned to its previously set position and the deflection value was 0.

In max-deflection mode (Group 6), polymerization shrinkage force measurements were conducted without any feedback from the rod and maximum deflection occurred in each composite. Deflection values of 0 and maximal deflection for each composite were measured in groups 1 and 6, respectively, and four intermediate deflection values were allocated to groups 2, 3, 4, and 5 (Table 2). The deflection of group 1 was zero. The deflection of group 6 was maximum. Before the experiment in this paper, through a number of pilot experiments, the author determined the deflections of group 2, group 3, group 4 and group 5 that could be distinct from each other and generate almost even intervals of shrinkage forces. The deflection values of each group for each material are shown in Table 2. In these groups, rod deflection was controlled by the feedback system. The measurements were repeated ten times for each group of materials. A schematic design of the experiments is shown in Figure 2.

Figure 1. Device for measurement of polymerization shrinkage force and deflection control; (A) load cell, (B) feedback sensor, (C) metal rod, (D) acrylic rod, (E) space for composite specimen placement, (F) acrylic base, (G) light source

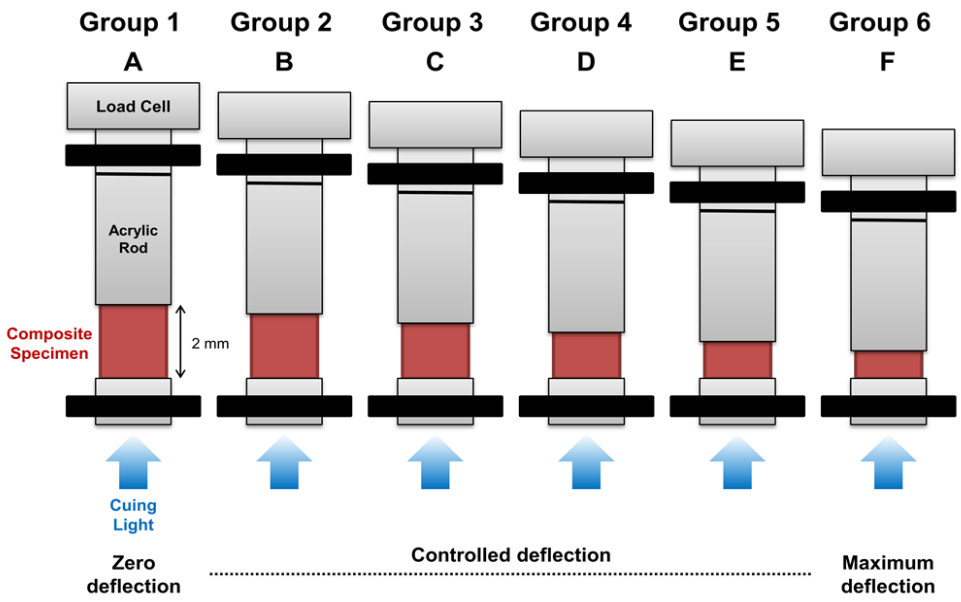


Figure 2. . Polymerization shrinkage force with various deflections; (A) zero deflection (B-E) controlled deflections (F) maximum deflection

Table2. The deflection values (μm) of each group for all materials at polymerization shrinkage force test

Materials	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
SDR®	0	9	10	11	12	14
EcuSphere-Shape	0	10	11	12	13	14
Tetric N-Ceram® Bulk Fill	0	6	7	8	9	11
CLEARFIL™ AP-X	0	7	8	9	10	11
Filtek™ Z350 XT	0	6	7	8	9	10

4. Measurement of Linear Polymerization Shrinkage

Polymerization shrinkage was measured using a custom-made Linometer (R&B Inc, Daejon, Korea) following the procedures previously described by Kim and Park. (Kim and Park, 2014) Resin specimens in equal amounts were prepared by applying composite resin to a cylindrical mold with a diameter of 4.5 mm and a depth of 1.3 mm. The resin specimens were placed on the metal disk of a custom-made Linometer (R & B Inc., Daejon, Korea) and covered with a glass slide; the metal disk and the glass slide were covered with a thin coating of glycerin gel to prevent adhesion. An LED-type light-curing unit (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein, 800 mW/cm^2) was placed 1 mm above the glass slide, and the material was light cured for 20 seconds. As the light irradiation progresses, the composite resin shrinks in the direction of the light, and the metal disk moves together with the composite resin; the measured value of this movement was stored in a computer. Polymerization shrinkage was measured for 120 seconds from the start of light irradiation 8 times.

5. Measurement of Flexural Modulus

This test was carried out in accordance with ISO 4049. Specimens (2 ± 0.1) mm × (2 ± 0.1) mm × (25 ± 2.0) mm in size were prepared. Each specimen was light cured along its length using a light-curing unit (Bluephase N, Ivoclar Vivadent, 800 mW/Cm^2) for three 20-second exposures. If there were bubbles, voids, or other defects on the surface, a new

specimen was made. The specimens were stored for 24 ± 1 hours in distilled water at 37 ± 1℃ until the test. The size (width, height) of the specimen was measured with internal and external calipers, and the specimens were wet ground slightly with 320-grit silicon carbide paper on all four surfaces to reduce flash. Maximum load and maximum deflection were measured with a three-point bending test at a cross-head speed of 0.75 ± 0.25 mm/min on a universal testing machine (Instron 3366, Norwood, MA, USA). After the measurement, flexural moduli were calculated in GPa using the following equation:

$$E_{flexural} = \frac{FL^3}{4wdh^3}$$

where $E_{fleural}$ = flexural modulus, F = maximum load, L = span length, w = specimen width, h = specimen height, and d = deflection.

6. Statistical analysis

For each material, shrinkage force values of the six groups were compared using one-way ANOVA and Tukey's post hoc tests at a 95% confidence level. One-dimensional linear regression analyses were performed to explore the relationship between polymerization shrinkage force and deflection in each material. Pearson's correlation analyses were done with 95% confidence to evaluate the relationship between polymerization shrinkage force and linear polymerization shrinkage of the materials in each group, between polymerization shrinkage force and flexural modulus of the materials in each group, and between linear polymerization shrinkage and flexural

modulus of the materials. Statistical analyses were conducted using PASW statistics 18 software (SPSS for Windows: SPSS Inc., Chicago, IL, USA).

III. RESULTS

For the SDR® material, when the deflection increased from 0 μm to 14.3 μm, the polymerization shrinkage force decreased from 6.5 kgf to 3.0 kgf (Figure 3, Table 3). There were statistically significant differences in the shrinkage force value between the groups ($p < 0.05$, Table 3). An equation of $y = -0.2229x + 6.3686$ ($R^2 = 0.9082$) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4).

For the EcuSphere-Shape material, when the system displacement increased from 0 μm to 14.4 μm, the polymerization shrinkage force decreased from 6.06 kgf to 2.73 kgf (Figure 3, Table 3). There were statistically significant differences in the shrinkage force value between the groups ($p < 0.05$, Table 3). An equation of $y = -0.2435x + 6.8696$ ($R^2 = 0.8501$) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4).

For the Tetric N-Ceram® Bulk Fill material, when the system displacement increased from 0 μm to 10.2 μm, the polymerization shrinkage force decreased from 4.44 kgf to 2.00 kgf (Figure 3, Table 3). There were statistically significant differences in the shrinkage force value between the groups ($p < 0.05$, Table 3). An equation of $y = -0.2116x + 4.7669$ ($R^2 = 0.7525$) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4).

For the CLEARFIL™ AP-X material, when the system displacement increased from 0 μm to 10.7 μm, the polymerization shrinkage force decreased from 4.73 kgf to 1.94 kgf (Figure 3, Table 3). There were statistically significant differences in the shrinkage force value between the groups ($p < 0.05$, Table 3). An equation of $y = -0.2201x + 5.0473$ ($R^2 = 0.7609$) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4).

For the Filtek™ Z350 XT material, when the system displacement increased from 0 μm to 10 μm, the polymerization shrinkage force decreased from 3.94 kgf to 1.83 kgf (Figure 3, Table 3). There were statistically significant differences in the shrinkage force value between the groups ($p < 0.05$, Table 3). An equation of $y = -0.1675x + 4.0691$ ($R^2 = 0.7397$) was acquired via regression analysis to express the relationship between polymerization force and deflection value (Figure 4).

There were significant differences in polymerization shrinkage forces between materials in each group (Table 3). There were also significant differences in linear polymerization shrinkage and flexural modulus between materials ($p < 0.05$) (Table 4). The Pearson product-moment correlation coefficients between the polymerization shrinkage force and the linear polymerization shrinkage in each group ranged from 0.641 (Group 4) to 0.925 (Group 6). The Pearson product-moment correlation coefficients between the polymerization shrinkage force and flexural modulus ranged from -0.444 (Group 5) to -0.776 (Group 6) (Table 5). The Pearson product-moment correlation coefficient between linear polymerization shrinkage and flexural modulus was -0.848 ($p < 0.001$).

Table 3. Mean (SD) of polymerization shrinkage force (kgf)

Materials	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
SDR®	6.5(0.8) ^{Cd}	4.7(0.6) ^{BCc}	4.3(0.5) ^{BCbc}	4.1(0.6) ^{Cbc}	3.6(0.7) ^{Cab}	3.0(0.3) ^{Ba}
EcuSphere-Shape	6.1(0.5) ^{Ce}	4.9(0.7) ^{Cd}	4.4(0.8) ^{Ccd}	4.0(0.6) ^{BCbc}	3.4(0.8) ^{BCab}	2.7(0.2) ^{Ba}
Tetric N-Ceram® Bulk Fill	4.4(0.6) ^{ABd}	3.9(0.6) ^{Acd}	3.7(0.6) ^{ABc}	3.2(0.7) ^{Abc}	2.7(0.6) ^{ABab}	2.0(0.2) ^{Aa}
CLEAR -FIL™ AP-X	4.7(0.2) ^{Be}	4.1(0.5) ^{ABd}	3.6(0.4) ^{ABcd}	3.3(0.8) ^{ABbc}	2.8(0.5) ^{ABCb}	1.9(0.3) ^{Aa}
Filtek™ Z350 XT	3.9(0.7) ^{Aa}	3.5(0.5) ^{Abc}	3.1(0.5) ^{Ab}	3.0(0.4) ^{Ab}	2.2(0.6) ^{Aa}	1.8(0.2) ^{Aa}

Groups with distinct upper case letters exhibit statistically significant differences in column and those with distinct lower case letters exhibit statistically significant differences in row ($p < 0.05$).

Table 4. Mean (SD) of Polymerization shrinkage (μm), Flexural Modulus (GPa)

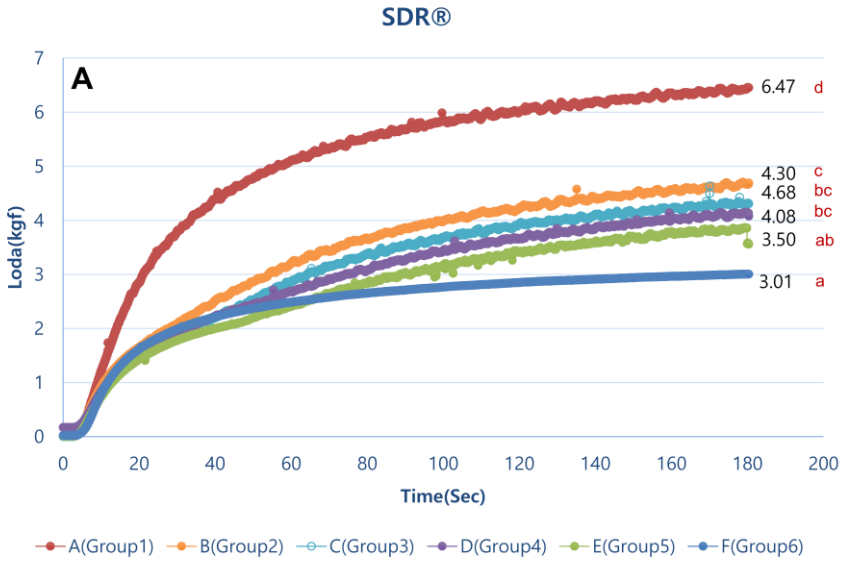
Materials	Linear Polymerization Shrinkage	Flexural Modulus
SDR®	31.6 (2.3) ^{e}	1.9(0.1) ^{a}
EcuSphere-Shape	22.2 (0.7) ^{d}	3.2(0.1) ^{b}
Tetric N-Ceram® Bulk Fill	16.1 (1.5) ^{c}	5.8(0.2) ^{c}
CLEAR -FIL™ AP-X	9.6 (0.8) ^{a}	13.3(0.6) ^{e}
Filtek™ Z350 XT	11.6 (0.8) ^{b}	7.0(0.3) ^{d}

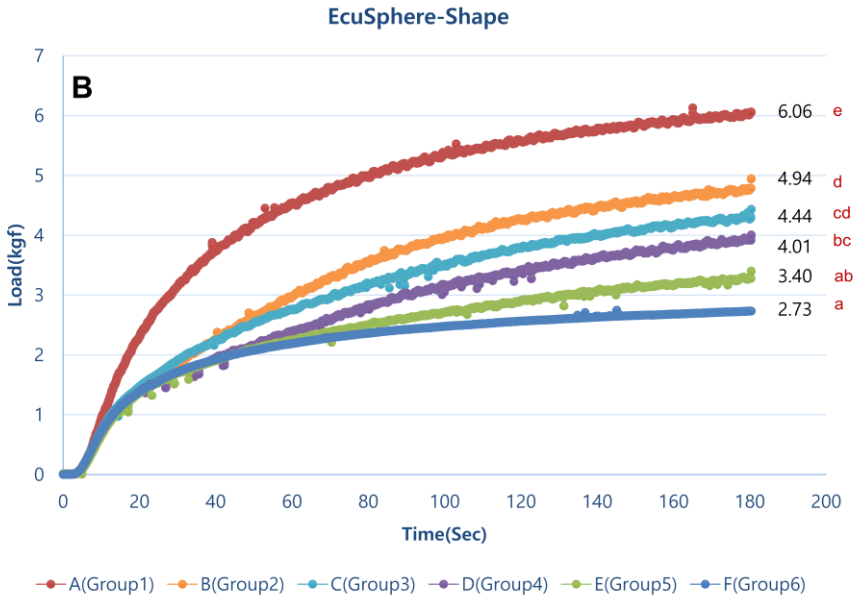
Figures in the parentheses are standard deviations.

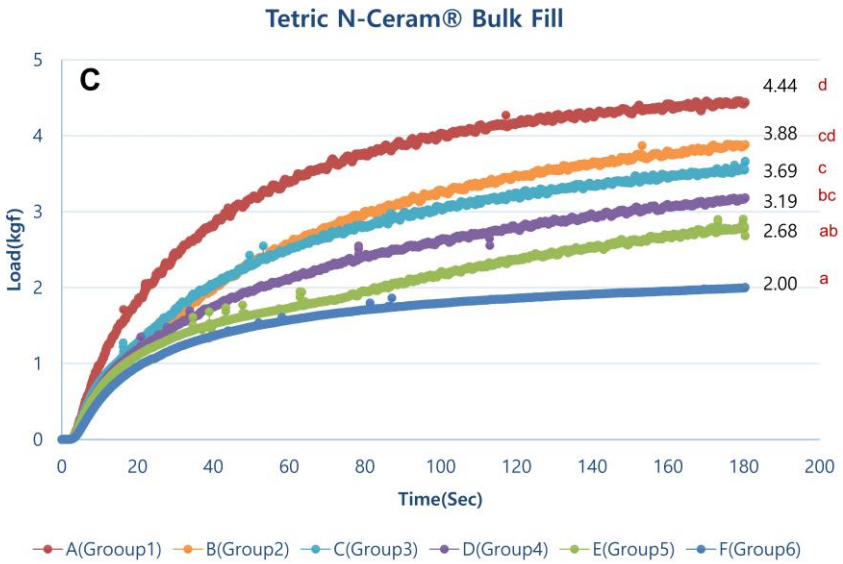
Table 5. Pearson correlations (significance) between the force measured in the six deflection modes and the linear polymerization shrinkage and flexural modulus

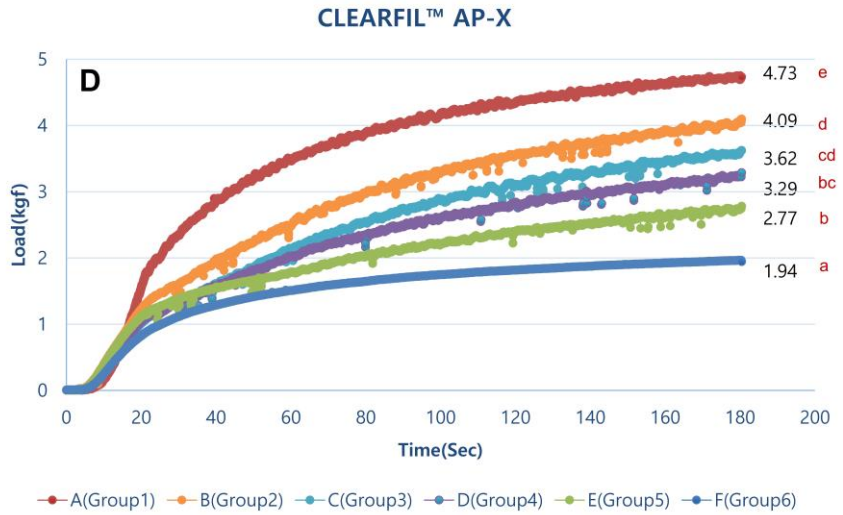
Polymerization Shrinkage Force	Linear Polymerization Shrinkage	Flexural Modulus
Group 1	0.908(0.000)	-0.642(0.000)
Group 2	0.775(0.000)	-0.605(0.000)
Group 3	0.773(0.000)	-0.514(0.001)
Group 4	0.641(0.000)	-0.449(0.004)
Group 5	0.649(0.000)	-0.444(0.004)
Group 6	0.925(0.000)	-0.776(0.000)

Figures in the parentheses are significance.









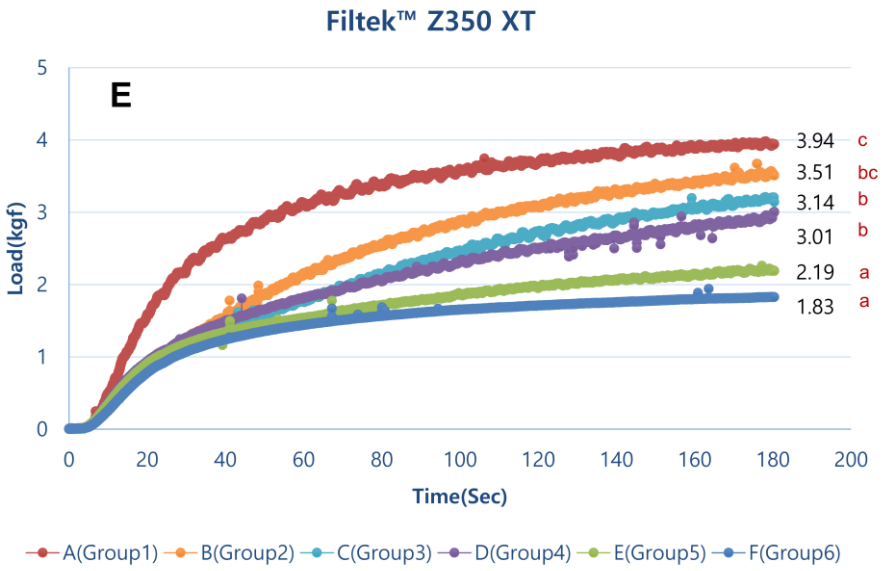
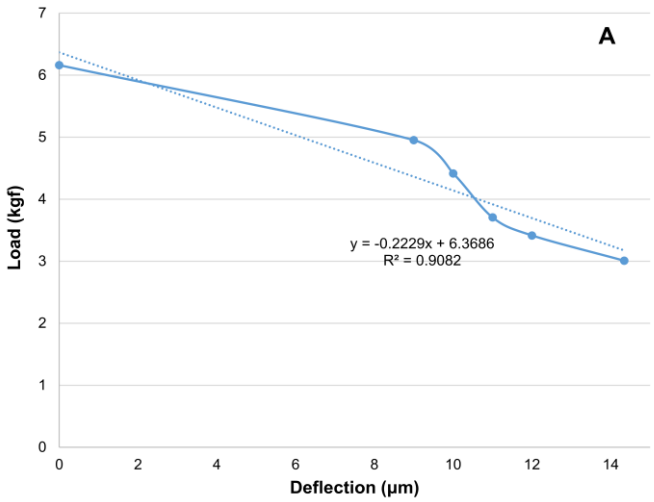
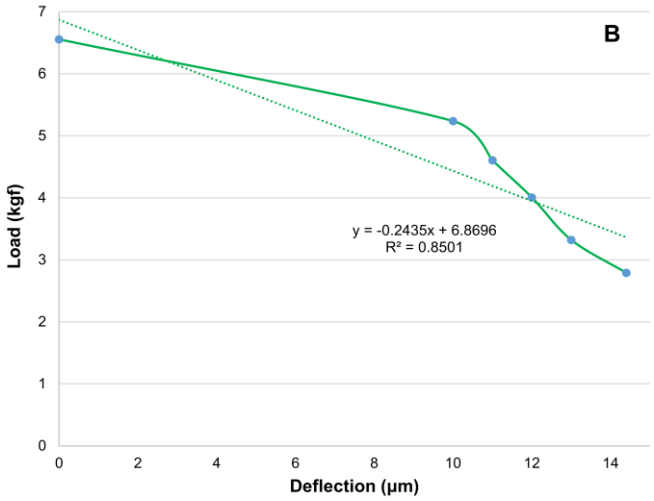
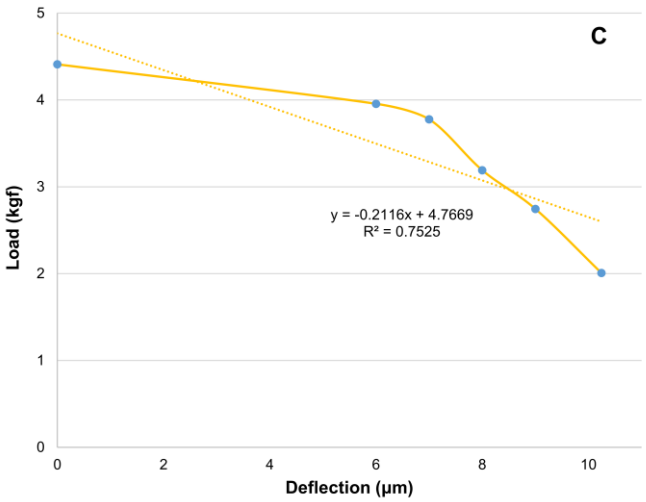


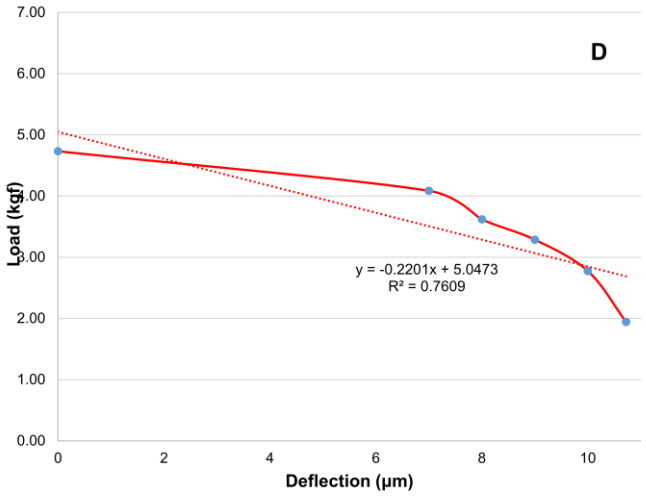
Figure 3. Time vs. force graphs for all composites (A) SDR®, (B) EcuSphere-Shape, (C) Tetric N-Ceram® Bulk Fill, (D) *CLEARFIL™ AP-X,* (E) Filtek™ Z350XT

(Differentletters exhibit statistically significant differences ($p < 0.05$).









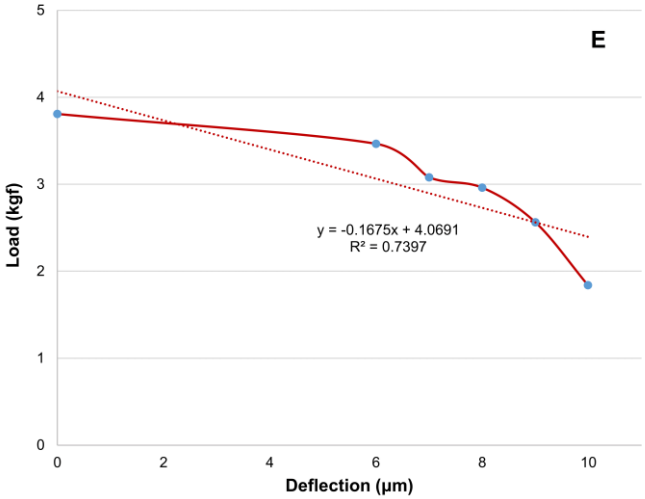


Figure 4. Deflection vs. force graphs with regression analysis (A) SDR®, (B) EcuSphere-Shape, (C) Tetric N-Ceram® Bulk Fill, (D) *CLEARFIL™ AP-X,* (E) Filtek™ Z35XT

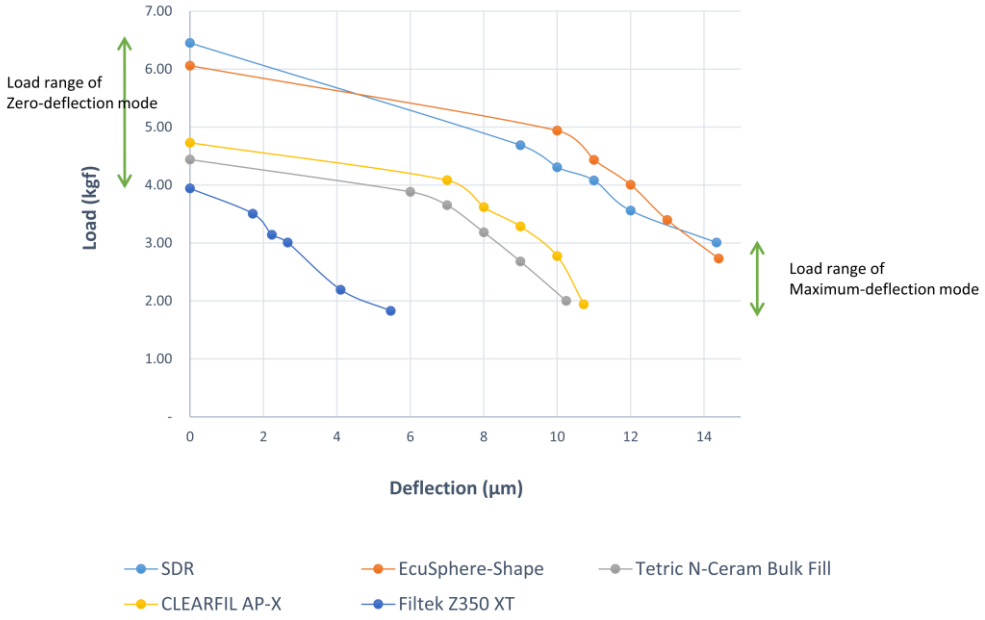


Figure 5. Deflection vs. force curves for all composites

IV. DISCUSSION

Polymerization shrinkage of composite resin causes problems such as cuspal deflection, (Andreasi Bassi et al., 2016; Kim and Park, 2011; Lee and Park, 2006; Prager et al., 2018; Tsujimoto et al., 2018) interferes with marginal and internal adaptations of composite restoration to tooth substance, (Han et al., 2016; Han and Park, 2017; Jung and Park, 2017; Kim and Park, 2014) and remains as a tensile residual force on the tooth, potentially lowering tooth fatigue strength. (Bathias, 2006; Ferracane, 2008) Initially high external and internal adaptations are exacerbated after undergoing fatiguing processes, such as simulated chewing and thermocycling, due to the residual forces on the composite resin. In addition, the degree of marginal and internal adaptations is related to the amount and degree of polymerization shrinkage. (Dietschi et al., 2002; Han et al., 2016; Jung and Park, 2017; Kim and Park, 2014; Rocca et al., 2012)

According to Watts & Satterthwaite, (Watts and Satterthwaite, 2008) the polymerization stress depends on both C-factor and composite mass in a compliance-allowed system. The volume of composite used in the present study was 63 mm^3, which was chosen to simulate Lee & Park's study (Lee and Park, 2006) as much as possible. The C-factor, which was 1.6, was set to simulate that of their MOD cavity as much as possible. In their study, the cuspal deflection in the premolar MOD cavity was 14.6-22.7 μm. In the present study, deflection ranged up to 15 μm, so the two studies are consistent.

The deflections and polymerization shrinkage forces were highly negatively correlated in all materials (Figure 4), and the first null hypothesis is rejected. With lower deflection, the system was stiffer, causing more force due to difficulties in polymerization shrinkage. On the other hand, with higher deflection, the system was more flexible, and it accommodated some of the polymerization shrinkage, thus reducing the relative force.

In this experiment, the polymerization shrinkage force and linear polymerization shrinkage were positively correlated to a moderate to high degree in all groups (Table 5). The Pearson correlation coefficients between the polymerization shrinkage force and the flexural modulus in each group were in a moderate range, between -0.444 and -0.776 (Table 5). Thus, the second and third null hypothesis is rejected.

The present study showed that deflection is highly negatively correlated with polymerization shrinkage force (Figure 4) and the polymerization shrinkage force is highly correlated with the amount of polymerization shrinkage (Table 5). This is consistent with a previous study in which the amount of polymerization shrinkage and cuspal deflection were highly correlated. (Lee and Park, 2006).

The results of this study showed that linear polymerization shrinkage had a stronger effect on polymerization shrinkage force than flexural modulus in all groups (Table 5). Polymerization shrinkage itself is the fundamental cause of the polymerization shrinkage force. Flexural modulus, on the other hand, limits the proportion of the polymerization shrinkage force that is generated by polymerization shrinkage. Thus, although linear polymerization shrinkage and flexural modulus affect shrinkage force, the amount of

shrinkage itself seems to be more influential in all groups. This is consistent with a previous study by Kim & Park, (Kim and Park, 2011) in which a moderate correlation was found between flexural modulus and cuspal deflection. However, Tujimoto et al. reported that no significant relationship was found between the two. (Tsujimoto et al., 2018) The differences may be attributable to differences in the materials used. In the present study, the Pearson correlation coefficient between polymerization shrinkage and elastic modulus was -0.848. The high negative correlation between the two may affect polymerization shrinkage force and deflection, and resulted in a moderate correlation of elastic modulus in the present study.

As for the relationship between C-factor, polymerization shrinkage, and internal adaptation, Han et al. (Han et al., 2016) reported that internal adaptation in a high-C-factor cavity is inferior to that in a low-C-factor cavity for both conventional and bulk-filled composites; furthermore, polymerization stress under the compliance-allowed condition (Group 6 in the present study) was significantly correlated with internal adaptation in both high- and low-C-factor cavities. The difference in polymerization shrinkage force between materials was greater in zero-deflection mode (Group 1) and had a decreasing tendency as deflection increased (Figure 5, Table 3). The results of both the present study and the study by Han et al. imply that it is important to choose composites with lower polymerization shrinkage force in clinical situations with high C-factors and/or lower deflection values, such as Class I and V cavities. On the other hand, the choice of materials is less important in higher deflection situations such as in Class II cavities. Application of a clinical

technique that reduces polymerization shrinkage, such as reducing the amount of composite used with a base (Kwon et al., 2010) or a proper layering technique, (Jung and Park, 2017; Kim and Park, 2011; Kwon et al., 2012) is more important in such cases.

In a class II cavity, deflection of the tooth differs according to location and remaining tooth structure. The deflection of the cusp tip area is higher than that of the gingival or pulpal wall area. Considering the results of the present study, the polymerization shrinkage force would be lower at the cusp tip than in the pulpal or gingival wall area, and internal adaptation would differ between the areas. The study by Han and Park, (Han and Park, 2017) in which the internal adaptation of a class II cavity was evaluated using micro-CT, supports this assumption. In that study, the gingival floor of the proximal box and the pulpal floor of the cavity preparation had higher imperfect margins than did the buccal and lingual walls of the proximal box.

Considering the results of the present study, care should be taken when composites are placed on the pulpal floor, where deflection would be limited. According to Han et al., (Han et al., 2019) placing an intermediate layer between the pulpal floor and the composite material as a base or lining material increases the internal adaptation of a restoration by decreasing polymerization shrinkage stress. When flowable composites are considered to line a cavity floor, materials with low polymerization shrinkage stress should be chosen because of its effects on internal adaptation. (Han et al., 2019) In class II cavities, after placement of the intermediate layer, the importance of selecting materials with low polymerization shrinkage stress would be reduced because the composite is placed over the

intermediate layer which allows more deflection than the pulpal or gingival floor, and the differences in polymerization shrinkage between materials will be reduced. Proper layering technique would be more beneficial in this situation. (Jung and Park, 2017; Kim and Park, 2011; Kwon et al., 2012) Mechanically, when cuspal deflection occurs, the cavity wall receives a bending moment by the polymerization shrinkage of the composite resin. Using a base such as a glass ionomer shortens the moment arm to reduce the polymerization shrinkage force applied to the tooth.

SDR, a flowable-type bulk fill composite, showed the same or higher polymerization shrinkage force than other packable or packable-type bulk fill composites in all groups. This finding is consistent with previous studies which compared the polymerization shrinkage stress of bulk fill and packable composites.(Jang et al., 2015; Jung and Park, 2017; Kim and Park, 2014) However, when the polymerization shrinkage stress of SDR was compared with that of other flowables or flowable-type bulk fill materials, the polymerization shrinkage stress of SDR was relatively low in previous studies. (Han et al., 2019; Jang et al., 2015; Jung and Park, 2017) In this sense, SDR could be recommended as an intermediate material compared to other flowables.

V. CONCLUSION

There was a high negative correlation between allowable deflection and shrinkage force in all materials. For each material, the shrinkage force was the highest in zero-deflection mode, the force decreased as deflection increased, and the smallest force appeared in maximum-deflection mode.

The polymerization shrinkage force was highly correlated with the amount of polymerization shrinkage. On the other hand, the polymerization shrinkage force showed moderate negative correlation with flexural modulus. Polymerization shrinkage had a stronger effect on polymerization shrinkage force than flexural modulus in all groups. Thus, it is important to choose composites with lower polymerization shrinkage force in clinical situations with high C-factors and/or lower deflection values, such as Class I and V cavities.

When high deflection is expected, controlling composite volume with a base material or use of an incremental filling technique are recommended than trying to choose a composite with low polymerization shrinkage force.

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Abstract (IN KOREAN)

변위 허용 정도에 따른 복합레진 중합수축력의 변화

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(지도교수 박 성 호).

치아 수복재료로서 복합레진은 중합수축을 하고, 중합수축은 치아에 중합수축력을 야기한다. 치아가 받는 중합수축력은 허용되는 교두 변위의 양에 따라 달라지는데, 이 연구는 허용 변위에 따라 중합수축력이 어떻게 변하는지 연구하였다.

SDR® (Dentsply Caulk, Milford, DE, USA), EcuSphere-Shape (DMG, Hamburg, Germany), Tetric N-Ceram® Bulk Fill (Ivoclar Vivadent, Schaan, Liechtenstein), CLEARFIL™ AP-X (Kuraray Noritake Dental Inc., Sakazu, Kurashiki, Okayama, Japan), and Filtek™ Z350 XT (3M Dental Products, St Paul, MN, USA) 총 5개의 복합레진을

사용하였다.

치아의 교두 변위를 모사하면서 중합수축력을 측정할 수 있는 장치를 이용하였는데, 이 장치는 변위를 피드백 시스템으로 일정하게 유지하면서 중합수축력을 실시간으로 측정할 수 있도록 특별히 고안된 장치(R & B Inc., Daejon, Korea)다. 각 재료별로 총 6개의 변위 모드(최대 변위 모드, 제로 변위 모드, 4개의 조절된 변위 모드)가 실험에 사용되었다. 각 변위 모드마다 0.1초 간격으로 180초 동안 실시간으로 중합수축력을 측정하였다.

각 재료별로 중합수축량과 휨강도도 측정하였다. 각 재료별로, 6개 모드의 중합수축력 차이를 일원배치 분산분석과 Tukey's post hoc tests (95% 신뢰수준)로 비교하고, 각 그룹별로 5개의 재료간의 중합수축력 차이도 일원배치 분산분석과 Tukey's post hoc tests (95% 신뢰수준)로 비교하였다. 각 모드별 중합수축력의 중합수축량과 휨강도와의 상관 관계를 피어슨 상관계수 분석(95% 신뢰수준)로 비교하였다.

각 재료별로 제로 변위 모드에서 중합수축력은 가장 높았고, 변위의 허용 정도가 커짐에 따라 중합수축력은 점점 증가하여 최대 변위 모드에서 중합수축력은 최소값을 보였다. 모든 재료에서 중합수축력과 허용 변위는 강한 음의 상관관계를 보였다. 중합 수축력은 중합 수축량과 높은 양의 상관 관계를 보였다. 반면 중합 수축력은 휨계수와 중등도의 음의 상관 관계를 보였다. 중합

수축력은 모든 그룹에서 휨계수보다 중합수축량에 더 크게 영향을 받았다.

Class I이나 Class V와 같이 C-factor가 높고 변위값이 낮은 임상 상황에는 중합 수축력이 낮은 복합재를 선택하는 것이 중요하다. Base material을 쓰는 것은 변위가 가장 제한되어 복합레진의 중합수축력이 가장 높은 곳에서의 중합수축력을 낮추고, 복합레진의 양 자체를 줄여 중합수축력을 낮출 수 있다.

핵심되는 말: 교두변위, 복합레진, 중합수축량, 중합수축력, 중합수축응력, C-factor